Jensen's operator inequality and its application (Advanced Topics of Information Science and Functional Analysis)

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1. Introduction.

In 1980, Kubo-Ando [12] established the theory of operator means. Hansen and Hansen-Pedersen [9] considered the Jensen inequality in the frame of operator inequalities. (See also [5] and [11].) Under such situation, we discussed the invariance of the operator concavity by the transformation among functions related to operator means in [4]. As a simle application, we could prove the operator concavity of the entropy function $\eta(t) = -t\log t$ which was shown by Nakamura-Umegaki [13]. In the paper, we proposed the following characterization of the operator concavity:

Theorem A. *Let f be a continuous, real-valued function on $I = [0, r)$. Then the following conditions are mutually equivalent:*

(1) *f is operator concave on I, i.e.,*

$$f(tA + (1-t)B) \geq tf(A) + (1-t)f(B) \quad \text{for} \quad t \in [0,1] \quad \text{and} \quad A, B \in S(I),$$

where $X \in S(I)$ means that X is a selfadjoint operator whose spectrum is contained in I.

(2) *$f(C^*AC) \geq C^*f(A)C$ for all isometries C and $A \in S(I)$.*

(3) *$f(C^*AC + D^*BD) \geq C^*f(A)C + D^*f(B)D$ for all C, D with $C^*C + D^*D = 1$ and $A, B \in S(I)$.*

(4) *$f(PAP + P^\perp BP^\perp) \geq Pf(A)P + P^\perp f(B)P^\perp$ for all projections P and $A \in S(I)$.*

To show the utility of Theorem A, we review the following result in [4].

Theorem B. *Let f be a real-valued continuous function on $(0, \infty)$. Then f is operator concave if and only if so is f^*, where $f^*(t) = tf(t^{-1})$ for $t > 0$.*

In fact, suppose that f is operator concave. For arbitrary positive invertible operators A, B and positive numbers s, t with $s^2 + t^2 = 1$, we put $E = s^2A + t^2B$ and

$$X = sA^{1/2}E^{-1/2} \quad \text{and} \quad Y = tB^{1/2}E^{-1/2}.$$

Since $X^*X + Y^*Y = 1$, it follows from Theorem A (3) that

$$f(E^{-1}) = f(X^*A^{-1}X + Y^*B^{-1}Y) \geq X^*f(A^{-1})X + Y^*f(B^{-1})Y,$$

so that

$$f^*(E) = E^{1/2}f(E^{-1})E^{1/2} \geq s^2A^{1/2}f(A^{-1})A^{1/2} + t^2B^{1/2}f(B^{-1})B^{1/2},$$

that is, f^* is operator concave.

In addition, if we take $f(t) = \log t$, then $f^*(t) = -t\log t$. Hence, if one could the operator concavity of $\log t$, then that of the entropy function is easily obtained.

Concluding this section, we remark on the transformation $f \to f^*$. For this, we explain operator means briefly. A binary operation among positive operators on a Hilbert space m is called an operator mean (connection) if it is monotone and continuous from above in each variable and satisfies the transformer inequality. The principal result is the existence of an affine-isomorphism between the classes of all operator means and all nonnegative operator monotone functions on $(0, \infty)$, which is given by $f_m(t) = 1\ m\ t$ for $t > 0$. Thus $f_m^*(t) = t\ m\ 1$ is corresponding to the transpose m^* of m, i.e., $A\ m^*\ B = B\ m\ A$.

2. Yanagi-Furuichi-Kuriyama conjecture.

In this section, we apply Theorem A to an operator inequality related to a conjecture due to Yanagi-Furuichi-Kuriyama [14]. As a matter of fact, they proposed the following trace inequality: For $A, B \geq 0$,

$$\text{(1)} \qquad \mathrm{Tr}\ ((A+B)^s(A(\log A)^2 + B(\log B)^2)) \geq \mathrm{Tr}\ ((A+B)^{s-1}(A\log A + B\log B)^2)$$

for $0 \leq s \leq 1$.

We now prove it for $s = 0$ by showing the following operator inequality:

Theorem 1. *Let A and B be positive invertible operators on a Hilbert space. Then*

$$(A\log A + B\log B)(A+B)^{-1}(A\log A + B\log B) \leq A(\log A)^2 + B(\log B)^2.$$

Proof. It is similar to a proof of Theorem B. We put

$$C = A^{1/2}(A+B)^{-1/2} \quad \text{and} \quad D = B^{1/2}(A+B)^{-1/2}.$$

Then we have $C^*C + D^*D = 1$. We here note that the function t^2 is operator convex on the real line. Hence, if we put $X = \log A$ and $Y = \log B$, then it follows that

$$(C^*XC + D^*YD)^2 \leq C^*X^2C + D^*Y^2D,$$

cf. Theorem A (3). Arranging it by multiplying $(A+B)^{1/2}$ on both sides, we have the desired operator inequality.

In addition, we give a proof of (1) for $s = 1$. First of all, we note that an inequality

$$\text{(2)} \qquad \mathrm{Tr}\ (I(A|B)I(B|A)) \leq 0$$

holds for positive operators A and B, where $I(A|B) = A\log A - A\log B$ is an operator version of Umegaki's relative entropy. Actually we have

$$\begin{aligned}\mathrm{Tr}\ (I(A|B)I(B|A)) &= \mathrm{Tr}\ (A(\log A - \log B)B(\log B - \log A)) \\ &= -\mathrm{Tr}\ (A^{1/2}(\log A - \log B)B(\log A - \log B)A^{1/2}) \leq 0.\end{aligned}$$

Now a direct calculation shows that

$$\begin{aligned}&\mathrm{Tr}\ ((A+B)(A(\log A)^2 + B(\log B)^2) - (A\log A + B\log B)^2) \\ &= \mathrm{Tr}\ (AB(\log B)^2 + BA(\log A)^2 - 2(A\log A)(B\log B)).\end{aligned}$$

On the other hand, we have

$$\begin{aligned}&\mathrm{Tr}\ (I(A|B)I(B|A)) \\ &= \mathrm{Tr}\ (A(\log A)B\log B - A(\log A)B\log A - A(\log B)B\log B + A(\log B)B\log A) \\ &= \mathrm{Tr}\ (2A(\log A)B\log B - BA(\log A)^2 - AB(\log B)^2).\end{aligned}$$

Noting by (2), we have

$$\mathrm{Tr}\ ((A+B)(A(\log A)^2 + B(\log B)^2)) \geq \mathrm{Tr}\ ((A\log A + B\log B)^2),$$

which is the inequality (1) for $s = 1$.

Next we give two examples, which show that the above problem (1) can not be solved via operator inequalities in the following sense.

Theorem 2. *The following operator inequalities do not hold for positive invertible operators A and B in general:*

$$\text{(1)} \qquad (A+B)^{1/2}(A(\log A)^2 + B(\log B)^2))(A+B)^{1/2} \geq (A\log A + B\log B)^2.$$

$$\text{(2)} \quad (A(\log A)^2 + B(\log B)^2))^{1/2}(A+B)(A(\log A)^2 + B(\log B)^2))^{1/2} \geq (A\log A + B\log B)^2.$$

Proof. For the former, we take

$$A = \begin{pmatrix} 5 & 2 \\ 2 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} 5 & 1 \\ 1 & 1 \end{pmatrix}.$$

Then we have

$$\log A = \frac{\log(3+\sqrt{8})}{2\sqrt{8}} \begin{pmatrix} \sqrt{8}+2 & 2 \\ 2 & \sqrt{8}-2 \end{pmatrix} + \frac{\log(3-\sqrt{8})}{2\sqrt{8}} \begin{pmatrix} \sqrt{8}-2 & -2 \\ -2 & \sqrt{8}+2 \end{pmatrix},$$

$$\log B = \frac{\log(3+\sqrt{3})}{2\sqrt{3}} \begin{pmatrix} \sqrt{3}+2 & 1 \\ 1 & \sqrt{3}-2 \end{pmatrix} + \frac{\log(3-\sqrt{3})}{2\sqrt{3}} \begin{pmatrix} \sqrt{3}-2 & -1 \\ -1 & \sqrt{3}+2 \end{pmatrix}$$

and

$$(A+B)^{1/2} = \frac{\sqrt{11}}{10} \begin{pmatrix} 9 & 3 \\ 3 & 1 \end{pmatrix} + \frac{1}{10}\frac{\sqrt{11}}{10} \begin{pmatrix} 1 & -3 \\ -3 & 9 \end{pmatrix}.$$

Hence

$$X = (A+B)^{1/2}\{A(\log A)^2 + B(\log B)^2\}(A+B)^{1/2} - (A\log A + B\log B)^2$$

is approximated by

$$\begin{pmatrix} 0.2800534147 & 0.6060988713 \\ 0.6060988713 & 1.087423161 \end{pmatrix}$$

and $\det X \approx -0.06281927236 < 0$. Namely (1) does not hold for A and B.

For the latter, we take

$$A = \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}, B = \begin{pmatrix} 5 & 1 \\ 1 & 1 \end{pmatrix}.$$

Then we have

$$\log A = \frac{\log 3}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

and $\log B$ is the same as the above, so that

$$A(\log A)^2 + B(\log B)^2 = \begin{pmatrix} 15.40739329 & 5.007156201 \\ 5.007156201 & 2.62046225 \end{pmatrix}.$$

Hence its point spectrum is $\{0.8930894768, 17.13476606\}$ and its square root is as follows:

$$\begin{pmatrix} 3.799679761 & 0.9847979508 \\ 0.9847979508 & 1.284770503 \end{pmatrix}.$$

Thus the difference of the both sides

$$\{A(\log A)^2 + B(\log B)^2\}^{1/2}(A+B)\{A(\log A)^2 + B(\log B)^2\}^{1/2} - (A\log A + B\log B)^2$$

is approximated by

$$\begin{pmatrix} 8.760452694 & -1.019211361 \\ -1.019211361 & -0.0425050649 \end{pmatrix}.$$

Namely (2) does not hold for A and B.

In a private communication with Professor Yanagi, we knew this conjecture last autumn. Very recently we were given an oportunity to read a preprint [9] by Furuta, related to Theorem 2. The authors would like to express their thanks to Professor Furuta for his kindness of sending it.

3. Jensen's operator inequalities.

Recently, F.Hansen and G.K.Pedersen [13] reconsidered the preceding results in [12, 11] by themselves, which is along with Theorem A. (See also [10].)

Hansen-Pedersen's theorem. *The following conditions are all equivalent to that f is operator convex on $\mathcal{I}$:*

(i) $f\left(\sum_{k=1}^{n} C_k^* A_k C_k\right) \le \sum_{k=1}^{n} C_k^* f(A_k) C_k$ *for all selfadjoint A_k with $\sigma(A_k) \subset \mathcal{I}$ and C_k with* $\sum_{k=1}^{n} C_k^* C_k = 1$.

(ii) $f(C^*AC) \le C^* f(A) C$ *for all selfadjoint A with $\sigma(A) \subset \mathcal{I}$ and isometries C.*

(iii) $Pf\big(PAP + s(1-P)\big) \le Pf(A)P$ *for all selfadjoint operators A with $\sigma(A) \subset \mathcal{I}$, scalars $s \in \mathcal{I}$ and projections P.*

Now we synthesize Jensen's operator inequality. Among others, a theorem due to Davis [6] and Choi [5] is included as the fifth condition. (See also Ando [1].)

Theorem 3. *Let f be a real function on an interval $\mathcal{I}$, A or A_k a selfadjoint operator with $\sigma(A), \sigma(A_k) \subset \mathcal{I}$, and H or K a Hilbert space. Then the following conditions are mutually equivalent:*

(i) *(1) f is operator convex on $\mathcal{I}$.*

(ii) $f(C^*AC) \le C^* f(A) C$ *for all $A \in B(H)$ and isometries $C \in B(K,H)$.*

(ii') $f(C^*AC) \le C^* f(A) C$ *for all A and isometries C in $B(H)$.*

(iii) $f(\sum_{k=1}^{n} C_k^* A_k C_k) \le \sum_{k=1}^{n} C_k^* f(A_k) C_k$ *for all $A_k \in B(H)$ and $C_k \in B(K,H)$ with* $\sum_k C_k^* C_k = 1_K$.

(iii') $f(\sum_{k=1}^{n} C_k^* A_k C_k) \le \sum_{k=1}^{n} C_k^* f(A_k) C_k$ *for all A_k, $C_k \in B(H)$ with* $\sum_k C_k^* C_k = 1_H$.

(iv) $f(\sum_{k=1}^{n} P_k A_k P_k) \le \sum_{k=1}^{n} P_k f(A_k) P_k$ *for all A_k, and projections $P_k \in B(H)$ with* $\sum_k P_k = 1_H$.

(v) $f(\Phi(A)) \le \Phi(f(A))$ *for all unital positive linear map Φ between C^*-algebras $\mathcal{A}, \mathcal{B}$ and all $A \in \mathcal{A}$.*

Proof. **(i)⇒(ii):** Take $B = B^* \in B(K)$ with $\sigma(B) \in \mathcal{I}$. For $P = \sqrt{1_H - CC^*}$, putting

$$X = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix} \in B(H \oplus K),\ U = \begin{pmatrix} C & P \\ 0 & -C^* \end{pmatrix}, V = \begin{pmatrix} C & -P \\ 0 & C^* \end{pmatrix} \in B(K \oplus H, H \oplus K),$$

we have

$$C^*P = \sqrt{1_K - C^*C}C^* = 0 \in B(H,K), \;\; PC = C\sqrt{1_K - C^*C} = 0 \in B(K,H),$$

so that both U and V are unitaries. Since

$$U^*XU = \begin{pmatrix} C^*AC & C^*AP \\ PAC & PAP + CBC^* \end{pmatrix}, \qquad V^*XV = \begin{pmatrix} C^*AC & -C^*AP \\ -PAC & PAP + CBC^* \end{pmatrix},$$

then the operator convexity of f implies

$$\begin{aligned}
\begin{pmatrix} f(C^*AC) & 0 \\ 0 & f(PAP + CBC^*) \end{pmatrix} &= f\begin{pmatrix} C^*AC & 0 \\ 0 & PAP + CBC^* \end{pmatrix} \\
&= f\left(\frac{U^*XU + V^*XV}{2}\right) \\
&\le \frac{f(U^*XU) + f(V^*XV)}{2} = \frac{U^*F(X)U + V^*f(X)V}{2} \\
&= \begin{pmatrix} C^*f(A)C & 0 \\ 0 & Pf(A)P + Cf(B)C^* \end{pmatrix}.
\end{aligned}$$

Thus we have **(ii)** by seeing the $(1,1)$-components.

(ii)$\Rightarrow$(iii): Putting

$$\tilde{A} = \begin{pmatrix} A_1 & & \\ & \ddots & \\ & & A_n \end{pmatrix} \in B(H \oplus \cdots \oplus H), \qquad \tilde{C} = \begin{pmatrix} C_1 \\ \vdots \\ C_n \end{pmatrix} \in B(K, H \oplus \cdots \oplus H),$$

we have $\tilde{C}^*\tilde{C} = 1_K$. It follows from (ii) that

$$f\left(\sum_{k=1}^n C_k^* A_k C_k\right) = f\left(\tilde{C}^*\tilde{A}\tilde{C}\right) \le \tilde{C}^* f(\tilde{A})\tilde{C} = \sum_{k=1}^n C_k^* f(A_k) C_k.$$

(iii)$\Rightarrow$(v): Considering the universal enveloping von Neumann algebras and the uniquely extended linear map, we may assume that $\mathcal{A}$ is a von Neumann algebra. Thereby a selfadjoint operator $A \in \mathcal{A}$ can be approximated uniformly by a simple function $A' = \sum_k t_k E_k$ where $\{E_k\}$ is a decomposition of the unit $1_{\mathcal{A}}$. Since $\sum_k \Phi(E_k) = 1_{\mathcal{B}}$ by the unitality of Φ, then applying **(iii)** to $C_k = \sqrt{\Phi(E_k)}$, we have

$$f(\Phi(A')) = f\left(\sum_k t_k \Phi(E_k)\right) \le \sum_k f(t_k)\Phi(E_k) = \Phi\left(\sum_k f(t_k) E_k\right) = \Phi(f(A')).$$

The continuity of Φ implies (v).

Since (v) implies (iv) obviously, we next show **(iv)⇒(i)**: Putting

$$X = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}, P = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, U = \begin{pmatrix} \sqrt{1-t} & -\sqrt{t} \\ \sqrt{t} & \sqrt{1-t} \end{pmatrix},$$

we have

$$\begin{aligned} &\begin{pmatrix} f((1-t)A+tB) & \\ & f((1-t)B+tA) \end{pmatrix} \\ &= f(PU^*XUP + (1-P)U^*XU(1-P)) \\ &\leq PU^*f(X)UP + (1-P)U^*f(X)U(1-P)) \\ &= \begin{pmatrix} (1-t)f(A)+tf(B) & \\ & (1-t)f(B)+tf(A) \end{pmatrix}, \end{aligned}$$

so that f is operator convex.

Consequently, we proved the equivalence of (i) - (v). To complete the proof, we need **(ii')⇒(iii')** because it is non-trivial in (i) ⇒ (ii) ⇒ (ii') ⇒ (iii') ⇒ (iv) ⇒ (i).

Modifying the proof in [7], we can show **(ii')⇒(iii')**. We may assume $n = 2$. Putting

$$\tilde{X} = \begin{pmatrix} A_1 & & & \\ & A_2 & & \\ & & A_2 & \\ & & & \ddots \end{pmatrix}, \tilde{V} = \begin{pmatrix} C_1 & 0 & \cdots & & \\ C_2 & 0 & \cdots & & \\ 0 & 1 & 0 & \cdots & \\ \vdots & \ddots & \ddots & \ddots & \end{pmatrix} \in B(H \oplus H \oplus \cdots),$$

we have $\tilde{V}^*\tilde{V} = 1$ and

$$\begin{aligned} \begin{pmatrix} f(C_1^*A_1C_1 + C_2^*A_2C_2) & & \\ & f(A_2) & \\ & & \ddots \end{pmatrix} &= f(\tilde{V}^*\tilde{X}\tilde{V}) \leq \tilde{V}^*f(\tilde{X})\tilde{V} \\ &= \begin{pmatrix} C_1^*f(A_1)C_1 + C_2^*f(A_2)C_2 & & \\ & f(A_2) & \\ & & \ddots \end{pmatrix}. \end{aligned}$$

□

Remark 1. (1) Theorem 3 includes the above two Jensen's operator inequalities. An essential part of the proof for the Hansen-Pedersen-Jensen inequality is to show that **(1)** implies **(2)**. In fact, suppose **(1)** and $C^*C \leq 1$. Then, putting $D = \sqrt{1 - C^*C}$, we have by **(iii')** and $f(0) \leq 0$ that

$$f(C^*AC + D0D) \leq C^*f(A)C + D^2f(0) \leq C^*f(A)C.$$

(2) Note that the property either 'isometric' or 'unital' assures the spectral invariance as follows: *If* $m \leq A \leq M$, *then* $m \leq C^*AC \leq M$ *and* $m \leq \Phi(A) \leq M$ *for any isometry* C *and a unital positive linear map* Φ.

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